Rapid Response Concentration-Controlled Desorption of Activated Carbon to Dampen Concentration Fluctuations

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Fluctuations in concentration of organic vapors in gas streams that are treated by devices such as biofilters or oxidizers make it challenging to remove the vapors from the gas streams in an efficient and economic manner. Combining adsorption with concentration-controlled desorption provides an active buffer between the source of vapors and the control device for better control of concentration and flow rate of the gas stream that is treated by the secondary control device, hence further enhancing the performance or reducing the size of the devices. Activated carbon fiber cloth is used with microwave swing adsorption to remove methyl ethyl ketone (MEK) from air streams and then provide a readily controllable feed stream of that vapor in air at a specified concentration and gas flow rate with steady-state tracking desorption. MEK was captured with >99.8% efficiency during the adsorption cycle. The MEK concentration during the regeneration cycle was readily controlled at concentration set-points between 170 and 5000 ppmv, within relative standard deviations of 1.8 and 4.9%, respectively, and at 20% of the gas flow rate that was treated during the adsorption cycle. Such capability of the system allows the secondary control device to be optimized for select constant concentrations and low gas flow rates that is not possible without such pretreatment.

1. Introduction

Methods to remove organic vapors from gas streams are classified as recovery (e.g., adsorption, absorption, and condensation) or destruction (e.g., biofiltration and oxidation) techniques. Adsorption with regeneration is a desirable means to control the emissions of organic vapors such as hazardous air pollutants (HAPs) and volatile organic compounds (VOCs) from air streams as it allows for capture, recovery and reuse of those vapors. However, when recovery and reuse of HAPs/VOCs is not technically or economically feasible, transforming the HAPs/VOCs with biological degradation or oxidation into more benign products can be more appropriate. Biofiltration and oxidation are attractive HAP/

VOC destruction techniques because they can convert organic vapors into carbon dioxide, water vapor, and/or biomass. However, fluctuations in concentration of the vapor and high gas flow rates of the gas stream to be treated makes it challenging for biofilters and oxidizers to operate efficiently. For instance, high organic vapor concentration can be toxic while low concentrations can cause starvation of microorganisms in a biofilter, which results in reduced biomass and removal efficiency of the HAPs/VOCs (*1−4*). Similarly, low organic vapor concentrations result in increasing the consumption of auxiliary fuel necessary to sustain the appropriate temperature when using oxidation. Designing a biofilter or an oxidizer to meet the maximum concentration in the gas stream and at the total gas flow rate that is generated by the source(s) can result in a larger control device than would be necessary to treat the average vapor concentration in the gas stream (*5*). Hence, there is a need to dampen the fluctuations in vapor concentration in gas streams and reduce the total gas flow rates that are treated by biofiltration or oxidation to allow for a more reliable, efficient, and cost-effective control system.

Unlike biofiltration, adsorption's ability to capture organic vapors is less sensitive to fluctuations in the concentration of organic vapor. For instance, previous testing of an activated carbon fiber cloth (ACFC) adsorber with a fluctuating VOC stream from a painting facility was able to capture >99% of the organic vapors by adsorption (*6*). Adsorbents such as granular activated carbon (GAC) have been used as biofilter packing material on which biofilm was grown to assist with buffering of the fluctuations in organic vapor concentration (*7−10*). A biofilter was operated with and without GAC that was mixed with compost to treat a fluctuating concentration of toluene in air. The removal efficiency of toluene was comparable to that in a biofilter without activated carbon due to the low buffering capacity of toluene's varying concentration by the GAC in the biofilter (*10*). This observation was attributed to the presence of water in the biofilter and the short gas-phase contact time in the vessel (*10*). When GAC was used as packing material in two biofilters to treat trichloroethylene (TCE) and tetrachloroethylene (PCE) separately, it was observed that 2.1% of the TCE and 1.1% of the PCE were removed by adsorption (*9*). These low removal efficiencies were attributed to the thickness of the biofilm on the GAC.

GAC was also used in a separate vessel to dampen the fluctuations of the vapor concentration upstream of a biofilter (*5*, *10*, *11*). Passage of air through the vessel was used to desorb toluene during the regeneration cycles. The GAC dampened the changes in toluene concentration that ranged from 0 to 1000 mg/m³ to about 300 mg/m³ (*10*). GAC was also used to dampen fluctuations in concentration of a mixture of toluene and acetone (*5*). Dampening efficiency decreased with increasing gas flow rate and depended on the composition of the vapors. The GAC reduced the fluctuations in toluene concentration that ranged from 0 to 100 ppmv to less than 10 ppmv. However, GAC did not dampen the fluctuation in acetone concentration at high concentrations. The effect of inlet concentration and empty bed contact time (EBCT) on dampening the fluctuation in toluene concentration was also investigated for a stream of toluene in air (*11*). The most effective dampening occurred at low concentration (210 ppmv) and high EBCT (10 s) and resulted in a negligible (<few ppmv) concentration fluctuation. However, the lowest amount of dampening occurred at high concentration (1000 ppmv) and low EBCT (1.5 s) and

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resulted in fluctuations in concentration between 100 and 1000 ppmv.

Two vessels containing GAC were operated in series with alternating adsorption and desorption cycles upstream of a biofilter (*12*, *13*). This approach dampened fluctuations in organic vapor concentration by controlling the duration of the adsorption and desorption periods while using air at ambient temperature to regenerate the GAC. The concentration of the organic vapor upstream of the adsorbers periodically fluctuated between target values of 200, 400, and 600 ppmv during organic loading periods and was set at a target value of 0 ppmv during the starvation period. After treatment with GAC, the fluctuation in concentration was reduced with an average relative standard deviation (RSD = standard deviation/mean) of 38% during the organic loading period and 51% during the starvation period.

Adsorption has also been used to concentrate organic vapors upstream of oxidizers (*14*, *15*). A rotating honeycomb of silica zeolite monolith was used as a concentrator upstream of a thermal oxidizer to increase cyclohexane vapor concentration by 10 times during hot air desorption (*15*). Another honeycomb zeolite concentrator successfully increased the concentration of semiconductor production related VOCs (e.g., isopropyl alcohol, acetone, propylene glycol methyl ether, and propylene glycol monomethyl ether acetate) by 6.5−19.5 times (*14*). However, in both systems, there was no active control of vapors concentration during the regeneration cycle, and the resulting vapor concentration was not controlled separately from the gas flow rate because the energy used to desorb the vapor was provided by the hot air carrier gas. It was reported that the ratio of vapor concentrations between the desorption and adsorption cycles was determined by the ratio of gas flow rate during those cycles (*14*).

Buffering of the vapor concentration upstream of biofilters and oxidizers has improved the ability of those devices to remove organic vapors from gas streams. However, such buffering can be improved by utilizing a system that independently controls the power applied to the adsorbent to desorb the vapor and the gas flow rate during the desorption cycle. This can be achieved with a microwave-swing adsorption steady-state tracking (MSA-SST) desorption system that is located upstream of a biofilter or oxidizer. The MSA-SST system is a fixed-bed system that rapidly controls the power that heats the adsorbent/adsorbate, resulting in controlled desorption of the vapor into a gas stream that has an independently controlled flow rate. Such capability allows devices that can operate downstream of the MSA-SST system to be designed and operated to process a much lower total gas flow rate and at a constant inlet vapor concentration. Hence, such a downstream device will be much smaller than is possible if the gas stream was not pretreated by the MSA-SST system. For example, a downstream biofilter will be much smaller and will sustain a much more stable microbial population because the microorganisms will not experience starvation during times when the source is not generating vapors (e.g., non-continuous sources) or toxic conditions if the concentration of the vapors becomes too high. A downstream oxidizer will also be much smaller and utilize less auxiliary fuel because of the lower total gas flow rate that needs to be treated and the vapor concentration will be tailored for treatment by oxidation. These unique features of the system will allow for the control of organic vapors more reliably and at lower costs.

Results presented here describe a revised MSA system (*16*) that operated to provide specific organic vapor concentrations at a separately controlled total gas flow rate. The MSA-SST system used activated carbon fiber cloth (ACFC) to adsorb methyl ethyl ketone (MEK) vapor from air streams during its adsorption cycles. The system then provided a
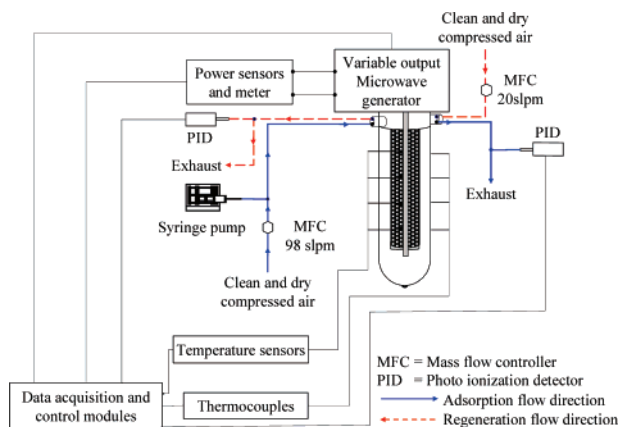

FIGURE 1. Experimental setup of the bench-scale MSA-SST system.

lower flow rate air stream with tailored vapor concentrations that could then be readily treated by devices such as a biofilter (i.e., 500 ppmv) or an oxidizer (5000 ppmv) during the MSA-SST's regeneration cycle.

2. Materials and Methods

2.1. Experimental Setup. The experimental setup consisted of a gas generation system, an adsorption/regeneration vessel, a microwave energy generation and propagation system, a gas detection system, and a data acquisition and control system (Figure 1). Details of the gas generation and detection systems, and the adsorption/regeneration vessel are provided elsewhere (*16*), but are briefly described here for clarity.

The main components of the gas generation system consisted of a syringe pump (KDS 200, KD Scientific) with a hypodermic needle (100 mL, Hamilton) to inject MEK in a dry, filtered air stream. The gas detection system consisted of a photoionization detector (PID, Modurae, RAE Systems). The ACFC adsorbent in the adsorption/regeneration vessel (ACC 5092−15, American Kynol Inc.) was 177 g and was rolled around a Teflon-coated fiberglass mesh to form a 45 cm long cartridge with an outer diameter of 6.5 cm and an inner diameter of 6 cm.

The microwave generation and propagation system consisted of a 2 kW switch-mode power supply (SM840E, Alter), a variable output 2 kW and 2.45 GHz microwave head (MH2.0W-S1, National Electronics), an isolator (National Electronics), a tuner (National Electronics), a waveguide to coaxial transition with a sliding short, and an aluminum conductor. The microwave generator provided the net power that was used to regenerate the adsorbent. The power was monitored with a dual directional coupler with 60 db attenuation (Mega Industries), two power sensors (8481A, Agilent), and a dual channel microwave power meter (E4419B, Agilent).

Temperature of the ACFC cartridge was measured with fluoroptic temperature sensors (FOT Lab kit, Luxtron) that were located 7.5, 19.5, 32.0, and 36.0 cm from the top of the cartridge. Fast response Type K thermocouples (Omega Inc., 0.25 mm in diameter), were also attached to the outer wall of the vessel, at the same vertical positions as the fluoroptic sensors, to monitor the temperature of the vessel's outer wall.

Outputs from the gas detection system, microwave generation system, and temperature measurement units were connected to a data acquisition and control system (National Instruments). A program was developed with Labview software (National Instruments Inc.) to provide continuous recording of the sensors' measurements and to control the power applied to the ACFC during the desorption cycle. A

proportional-integral-derivative algorithm was used to control the power applied to achieve the specified set-point vapor concentrations. The sensitivity of the algorithm was defined and tested to provide a constant vapor concentration during regeneration or to provide tracking of a dynamic set-point concentration during regeneration.

2.2. Experimental Methodology. The PID was calibrated with MEK (HPLC grade, >99.5% purity, Alfa Aesar) in air before each adsorption and regeneration test. Mass balances were used for the feed rates of the liquid MEK and air to determine the resulting concentrations of MEK vapor in the air streams that were detected by the PID. Multipoint calibrations occurred while the vapor generator was operated at the same gas flow rates as those used during the adsorption and regeneration tests to prevent any bias in the concentration measurements due to changes in gas flow rate and/or sample pressure. The gas generation system was then turned on and the gas stream bypassed the vessel until the organic vapor concentration achieved a specified steady-state value.

An adsorption cycle occurred by passing the vapor laden gas stream through the vessel at an MEK concentration of 500 ppmv and an inlet air flow rate of 98 slpm, which corresponded to an EBCT of 0.07 s. Nominal conditions for the laboratory where the experiments occurred were 23 °C and 101 kPa. The organic vapor laden air stream passed from the outside to the inside of the cartridge and then exited the vessel during the adsorption cycle. The concentration of the vapor at the outlet of the vessel was continuously monitored with the PID. Adsorption occurred until the outlet concentration reached a breakthrough concentration of 5% of the inlet concentration or until saturation of the adsorbent.

During regeneration, microwave power was applied while dry and filtered air flowed at 20 slpm in the reverse direction that was used for the adsorption cycles. The EBCT was 0.34 s during the regeneration cycles. The vapor in the gas stream that exited the vessel during the high and dynamic concentration tests could saturate the PID signal (i.e., >2000 ppmv). Hence, the gas stream was diluted to 20% of its initial outlet concentration with clean filtered air before detection by the PID. The outlet vapor concentration was monitored while power was applied to the cartridge. The vapor concentration was then compared to a predefined set-point value that represented the desired outlet vapor concentration. The proportional-integral-derivative feedback algorithm allowed the system to achieve the specified outlet concentration by controlling the microwave power applied to the ACFC that was based on set-points and measured vapor concentrations at the outlet of the vessel. An increase/decrease in the amount of power applied to the cartridge resulted in an increase/decrease in the temperature of the ACFC and an increase/decrease in the amount of adsorbate that was emitted from the adsorbent. Consequently, the power applied to the adsorbent acted as a correcting signal to reduce difference in the set-point and measured outlet concentrations, which resulted in a carefully controlled vapor concentration at an independently controlled total gas flow rate. A regeneration cycle continued while there was sufficient adsorbate in the cartridge to maintain the desired outlet vapor concentration and the adsorbent was below a maximum set-point of 170 °C. A regeneration cycle was then complete and the vessel was ready for its next adsorption cycle. The gravimetric mass of the adsorbent cartridge was measured before and after each adsorption and regeneration cycle (Metler, model BasBal).

Two methods were used to determine the amount of MEK that desorbed during each regeneration cycle to evaluate closure for the regeneration efficiency of the adsorber. "Method 1" is based on the gravimetric mass difference of the adsorbent cartridge before and after each regeneration cycle ($m_{d,1}$), while "Method 2" is based on the flow rate of air (Q_{reg}) and the concentration of MEK (C_{out}) at the outlet of the vessel during the regeneration cycles ($m_{d,2}$). Hence the subscripts "1" and "2" will refer to Methods 1 and 2, respectively.

$$m_{d,2} = \frac{Q_{reg}\,P\,MW}{R\,T} 10^6 \sum_{t=0}^{t=t_{reg}} (C_{out}) dt$$

where P is the total atmospheric pressure, MW is the molecular weight of the adsorbate, T is the temperature of the gas stream, t_{reg} is the regeneration time, and R is the ideal gas law constant.

The regeneration efficiency of the ACFC was then calculated based on the percentage of MEK desorbed from the ACFC.

$$\% \text{ desorbed} = \frac{(m_a - m_{d,i}) \times 100}{m_a}$$

Where the subscript i is equal to 1 or 2, corresponding to Methods 1 or 2 that were used to calculate m_d, and m_a refers to the mass of MEK adsorbed on the ACFC during the test.

3. Results and Discussion

The system captured MEK vapor at 500 ppmv with a collection efficiency, based on inlet and outlet concentration, of 99.8% until achieving 5% breakthrough. The MEK laden adsorbent was then regenerated to achieve a steady-state concentration of 500 ppmv or 5000 ppmv to provide a controlled feed for a potential biofilter or an oxidizer, respectively. No deterioration in the performance of the ACFC, based on adsorbate mass balances, was noticed after 11 adsorption and steady-state regeneration tests.

3.1. Low Steady-State Concentration Test Results. The MEK adsorbed onto the ACFC at 500 ppmv was first desorbed at a set-point of 500 ppmv and at 20 slpm air to simulate a controlled feed to a potential biofilter. The arithmetic mean and relative standard deviation (RSD) for the measured MEK concentration during the steady-state desorption test was 506 ppmv and 4.4%, respectively (Figure 2-A). The absolute relative difference (ARD) between the set-point ($C_{setpoint}$) and the measured (C_{out}) concentration ($1/N \sum^N [(|C_{out} - C_{setpoint}|/C_{setpoint}) \times 100]$) was 3.6%. The fluctuations in the concentration were due to the variation in power application and the intrinsic uncertainty in the PID readings. To assess the contribution of the two effects, the PID that was used to measure the concentration of a MEK stream from a calibrated compressed tank of MEK gas (Matheson Inc.). The RSD at an average MEK concentration of 500 ppmv that was provided by the compressed gas cylinder was 1%, which is 23% of the RSD that was experienced during the regeneration test.

The average temperature of the cartridge increased from ambient conditions (23 °C) to 154 °C within 1500 min (Figure 2-B). Temperature increase was slow at the beginning of the regeneration cycle. This is because a small variation in cartridge temperature results in larger changes in the adsorption capacity due to the larger loading of the MEK on the ACFC at the beginning of the regeneration cycle. As more MEK desorbed from the ACFC, more energy was needed to desorb the remaining adsorbate, and hence, the cartridge needed to be heated to a higher temperature. Adsorbate that was weakly attached to the adsorbent desorbed first, while the adsorbate present in the smallest micropores was more difficult to desorb because of those pores' stronger adsorption energies. The temperature of the vessel's wall also increased, but at a much slower rate, to a maximum value of 46 °C (Figure 2-B). Heating of the wall occurred due to convective and radiative heat transfer from the gas stream and cartridge.

Since the concentration of MEK exiting the vessel during the regeneration cycle was constant, the desorption rate
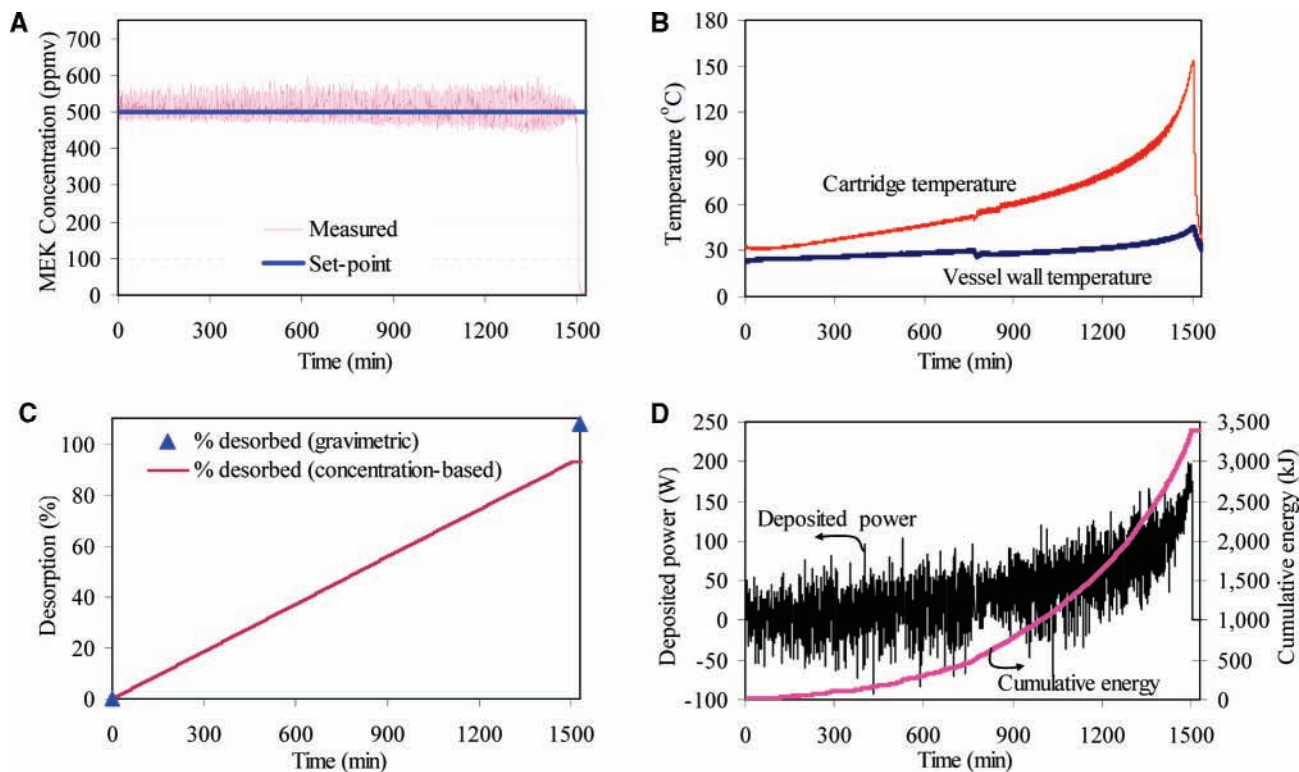
FIGURE 2. Low concentration regeneration test to achieve an outlet concentration of 500 ppmv. (A) The vessel's outlet vapor concentration with a set-point of 500 ppmv; (B) temperature of the ACFC and the vessel wall; (C) extent of regeneration of the ACFC; (D) power and cumulative energy deposited to the ACFC.

(amount of MEK desorbed per unit time) was also constant, and hence, the cumulative amount of MEK desorbed increased linearly with time (Figure 2-C) to a maximum of 93% of the adsorbed MEK (m_a). Based on weight difference, the desorbed MEK ($m_{d,1}$) was 108% of m_a, which also indicates almost complete regeneration of the ACFC during steady-state desorption conditions. The methods used to determine $m_{d,1}$ and $m_{d,2}$ agreed within 14%. This discrepancy is attributed to the uncertainties of possibly adsorbing water vapor onto the ACFC or desorbing MEK from the ACFC once it is exposed to ambient air when the cartridge was weighed. There are also uncertainties in the PID calibration, MEK concentration measurement, measurement of total air flow rate, and minor changes in environmental conditions (e.g., pressure and temperature of the laboratory) during the tests that occurred over 6 to 26 h.

The microwave power deposited to the cartridge was averaged over 1 min periods and is depicted in Figure 2-D. The negative power values are most likely due to technical limitations in power measurements caused by the pattern of wave propagation in the waveguide. The average power was 37.7 W, which corresponds to 3399 KJ or 60.7 KJ/g of MEK desorbed. The increase in the power deposited to the system, as regeneration proceeds, supports the above conclusion that it is more difficult to desorb the remaining adsorbate.

3.2. High Steady-State Concentration Test Results. An adsorption cycle removed 500 ppmv of MEK until the adsorbent was saturated to prepare for a desorption cycle with a set-point of 5000 ppmv outlet concentration at 20 slpm air to simulate a feed for an oxidizer. An MEK concentration of 5000 ppmv in the bulk air appears to be a conservative value for safe operating conditions as it represents 28% of its lower explosive limit (LEL = 1.8% by volume (*17*)) at ambient conditions and 31% of its LEL at 160 °C, as there is a slight decrease in the LEL as temperature increases from 25 to 160 °C. However, within the pores of the

adsorbent, MEK can form as a liquid. For example, the calculated mean concentration of MEK in the adsorbent's pores is 0.53 g/cm³ at ambient temperature when the equilibrium MEK concentration in the bulk gas is 500 ppmv. However, the maximum regeneration temperature is much less than the autoignition temperature for bulk MEK, which is 514 °C in air (*17*), and no explosions or fires were observed during steady-state desorption experiments. For oxidizers, the maximum allowable inlet concentration is 25% of LEL. Waste gas streams with concentrations exceeding this limit need to be diluted before entering the oxidizer (*18*) or may need to be treated as an auxiliary fuel (*19*). The average measured concentration during the steady-state desorption was 5004 ppmv with a RSD of 3.1% and an ARD of 2.3% (Figure 3-A). The figure also depicts the importance of tuning the parameters for the proportional-integral-derivative control algorithm. The RSD in the concentration for time <50 min was 4.6%. However, decreasing the integral coefficient of the control algorithm decreased the RSD in concentration to 1.8%. Tuning the parameters for the control algorithm resulted in a more stable concentration and resulted in a smoother temperature and power profile.

The average temperature of the cartridge increased from 24 to 159 °C during the regeneration cycle (Figure 3-B). The vessel wall temperature increased from ambient conditions to 53 °C with an average value of 35 °C. This value is higher than that obtained in the low steady-state concentration test because more power was used to heat the adsorbent, which transferred to the wall of the vessel.

The cumulative desorbed MEK ($m_{d,2}$) increased linearly with time to a maximum of 81% of the adsorbed MEK (m_a) during the previous adsorption cycle (Figure 3-C). Based on weight difference, the desorbed MEK ($m_{d,1}$) was 94% of m_a. The percent of MEK desorbed based on $m_{d,1}$ and $m_{d,2}$ agreed within 14%.
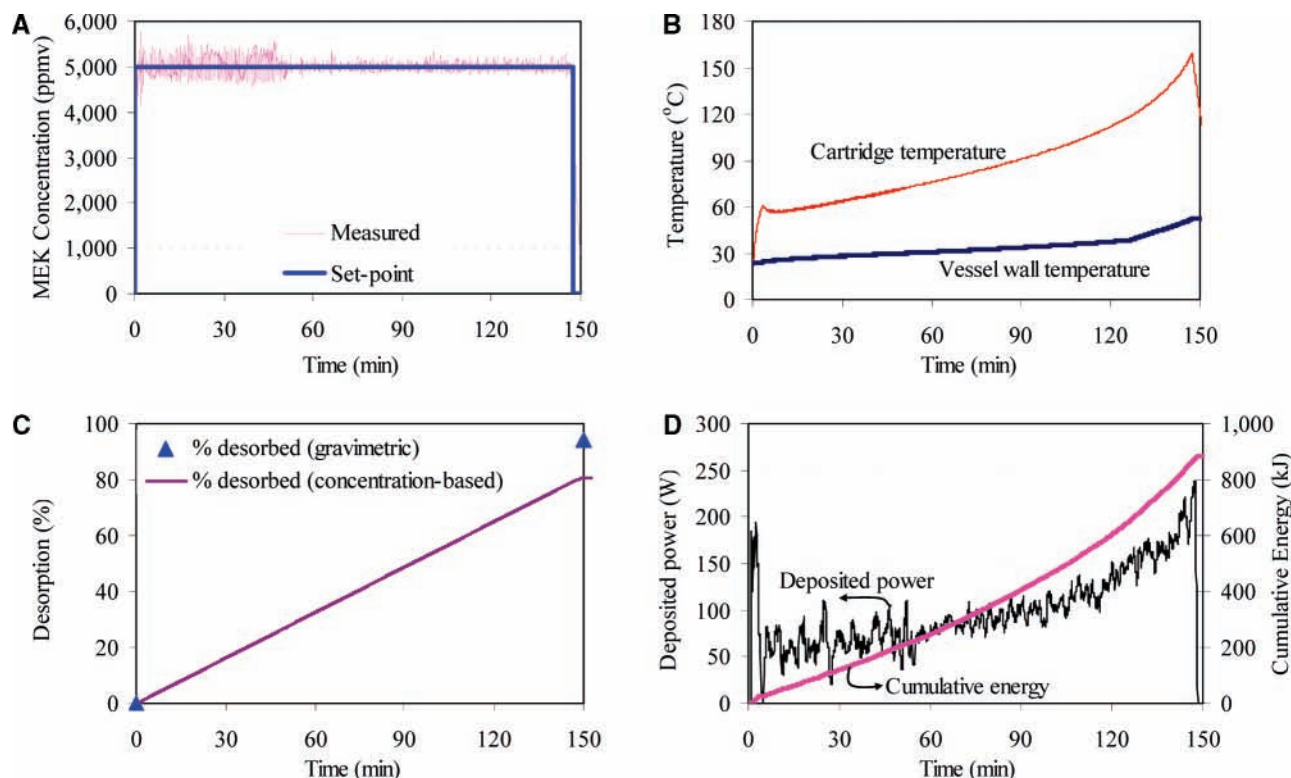
FIGURE 3. High concentration regeneration test results to achieve an outlet concentration of 5000 ppmv. (A) The vessel's outlet vapor concentration with a set-point of 5000 ppmv; (B) temperature of the ACFC and the vessel wall; (C) extent of regeneration of the ACFC; (D) Power and cumulative energy deposited to the ACFC.
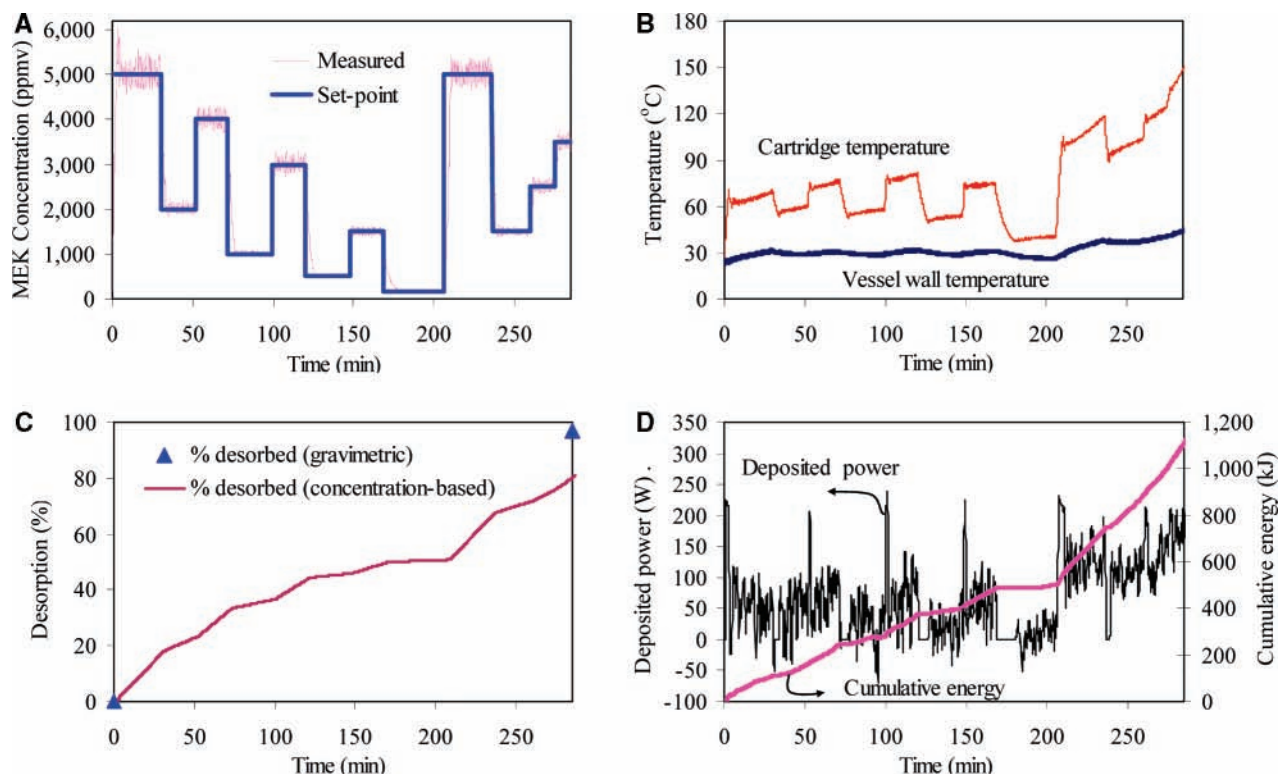

FIGURE 4. Regeneration test results during dynamic tracking of the specified outlet vapor concentration. (A) Vessel's outlet vapor concentration with a set-points ranging from 170 ppmv to 5000 ppmv; (B) temperature of the ACFC; (C) extent of regeneration of the ACFC; (D) power and cumulative energy deposited to the ACFC.

The average power deposited to the system was 99.6 W, which corresponds to 880 KJ or 16.1 KJ/g of MEK desorbed (Figure 3-D). The high concentration steady-state test utilized 2.6 times more power than the low concentration steady-state test, allowing for the higher rate of desorption, and hence, higher vapor concentration that was needed to match the concentration set-point. However, the total energy deposited and the energy deposited per unit mass of MEK

desorbed was 74% less than the corresponding values for the low concentration test because energy is applied to maintain the cartridge at the desorption concentration for less time.

3.3. Dynamic-Tracking Concentration Test Results. An adsorption cycle removed 500 ppmv of MEK until 5% breakthrough was achieved to prepare for a desorption cycle with dynamic tracking conditions. This desorption test caused the system to follow transient set-points for the outlet concentration (Figure 4), which demonstrates the flexibility of the system in terms of the quick response of the measured concentration to the variation in concentration set-point during regeneration. For example, the concentration of organic vapors and air flow rate for the feed stream to a biofilter can be adjusted separately to allow for a stable microbial population and efficient removal of the organic vapors from the gas stream. The organic vapor concentration and gas flow rate can also be adjusted upstream of an oxidizer to allow for safe and energy efficient oxidation of the vapors. The concentration set-point varied from 170 to 5000 ppmv, and the measured concentration rapidly followed the transient set-point (Figure 4-A). The average difference between set-point and the measured concentration ranged from 0 to 0.7%, while the RSD in measured concentration ranged from 2.8 to 3.9%, and the ARD between the set-point and the measured concentration ranged from 2.2 to 3.3%.

Variation in the temperature of the ACFC reflected the change in concentration set-point as the temperature increased from 23 to 152 °C (Figure 4-B). This response was more pronounced than the variation of the vessel's wall temperature that ranged from 23 to 45 °C.

The desorption rate of MEK rapidly increased or decreased with increasing or decreasing concentration set-point, respectively (Figure 4-C). By the end of the regeneration cycle, the cumulative MEK desorbed ($m_{d,1}$) increased to 82% of m_a. However, based on weight difference, the MEK desorbed ($m_{d,2}$) was 97% of m_a. The percent of MEK desorbed based on $m_{d,1}$ and $m_{d,2}$ agreed within 16%.

The average power deposited to the system was 66.2 W, which corresponds to 1,140 KJ or 22.2 KJ/g of MEK desorbed (Figure 4-D). The sharp spikes in power reflect the need to apply more power when changing from a low to a high outlet concentration set-point. Changing to a lower-concentration set-point results in a sudden decrease in power deposited to the system.

While the amounts of MEK adsorbed and desorbed were within 3.3% for the three test conditions, the power and energy consumption varied substantially. Based on the power and energy results, the high steady-state concentration test consumed the least amount of energy although it has the highest power output requirements. This is because the duration of the high steady-state concentration test was the shortest. Hence, it had the least amount of energy needed to maintain the temperature of the cartridge at the required desorption temperature and the least amount of heat loss from the ACFC during the regeneration cycle. However, the low steady-state concentration test had the highest desorption efficiency. This is because the lower concentration set-point allows the regeneration to proceed longer until the adsorbed MEK is insufficient at lower regeneration temperatures of the ACFC.

Overall these tests demonstrate that ACFC and microwave heating can be readily integrated and used as a buffer system by adsorbing organic vapor and then providing steady-state or dynamic-tracking vapor concentrations during the desorption cycle. The resulting low flow rate gas stream can then be more readily treated by auxiliary control technologies such as biofiltration or oxidation. Integration of the MSA-SST system with auxiliary devices will enhance the economic and removal efficiencies to control organic vapor emissions when recovery of the pollutants is not as favorable.

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